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WWVB Baseline Measurements: Summary, Findings and Recommendations

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

The National Institute of Standards and Technology (NIST) operates a 60-kHz timing signal transmitter, known as WWVB, at a site near Fort Collins, Colorado. This system has redundant transmitters and antenna systems and was thought to radiate about 13 kW. NIST commissioned the Naval Command, Control and Ocean Surveillance Center, Research, Development, Test and Evaluation Division (NRaD) to make baseline performance measurements that could support the design of a 6-dB upgrade. The measurements are reported in NRaD Technical Report 1693. This document provides a summary of the measurement results, a recommended upgrade configuration, and recommendations.

The recommended upgrade includes two new transmitters, use of 50-ohm coaxial transmission lines, and adjustable matching. The recommended upgrade will result in complete redundancy for ease of maintenance and will allow for the possibility of dual-array operation for further increases in radiated power. The major aspects of the recommended upgrade are given in section 5.6.

The recommendations are listed below.

1. Replace the insulators in the toploads and feed cages as soon as possible. Also replace the guy fail-safe insulators with a new fail-safe insulator of a different type.
2. Inspect and repair all electrical aspects of both antennas as required. The topload panels and downlead cages must be inspected. All electrical connections and jumpers should be taken apart, cleaned, repaired or replaced if necessary, and coated with conducting grease prior to reassembly.
3. The towers and guy wires should be inspected by structural experts.
4. Start the process of obtaining two AN/FRT–72 transmitters from the U.S. Navy as soon as possible.
5. Develop a plan for the recommended upgrade. This plan should consider transmitter physical location, floor loading, air conditioning loads, cooling air requirements, prime power availability, as well as the RF considerations such as transmission lines, power and voltage limitations, etc. The plan should include a time availability propagation analysis for the increased radiated power.

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1. OBJECTIVE

The National Institute of Standards and Technology (NIST) commissioned the Naval Command, Control and Ocean Surveillance Center (NCCOSC), Research, Development, Test and Evaluation Division (known as NRaD) to make baseline measurements of the WWVB 60-kHz time standard broadcast antenna systems during October 1994. The objective of this report is to summarize the measurement results, analyze findings, and provide resulting recommendations. The measurement details are described in NRaD Technical Report 1693 (Gish and Hansen, 1995). The objectives of this task were to determine the performance of the existing system and gather additional data required to support the design of a 6-dB upgrade. This report also identifies necessary antenna maintenance actions.

2. BACKGROUND

NIST, formerly the National Bureau of Standards, provides services that broadcast accurate time and frequency signals by several means. One of these services, known as WWVB, is a low-frequency (LF) 60-kHz broadcast from their Fort Collins transmitting site. This service was originally initiated from a site in Boulder, Colorado, in July 1956 and transmits time and frequency signals at 60 kHz primarily for the continental United States (CONUS). WWVB was moved to the Fort Collins site in July 1963. There was also an experimental very low-frequency (VLF) time signal on 20 kHz, known as WWVL, which was initiated in 1960 from a location at Sunset, Colorado. WWVL was moved to Fort Collins at the same time as WWVB (July 1963) but has since ceased operations (Viezbicke, 1971; Beehler and Lombardi, 1991).

Both WWVL and WWVB transmitting systems were designed and built by W.W. Brown around 1958. Since that time, there have been some modifications including changes to the ground system. Documentation for the antenna systems is sparse. Based on some old 60-kHz data, the antennas were thought to have 1-ohm total resistance and to be about 30-percent efficient. The radiated power (during pulse maximums) was thought to be about 13 kW. The initial objective for the upgrade is a 6-dB increase in radiated power to achieve about 50 kW radiated. This increase may be accomplished by increasing radiation efficiency and/or increasing transmitter power.

Two antennas are used for the WWVB LF broadcast. Both antennas are located approximately 1500 feet away from the transmitter building, but in opposite directions. Each has its own helix house containing the tuning helix and variometer. The antenna to the south was originally used for the 60-kHz broadcast and is still the primary antenna for this service. The north antenna was originally used for the now discontinued 20-kHz broadcast and is now used as the 60-kHz system backup antenna.

Two transmitters provide the WWVB broadcast. They are believed to have been built by modifying surplus military HF transmitters, and very little documentation is available. They are (somewhat affectionately) called “Old Blue”and “Old Grey” after the color of the cabinets. The transmitters are very different, but both are nominally rated at 50 kW. Originally the grey transmitter was used for the 60-kHz broadcast (WWVB) on the south antenna, and the blue transmitter was used for the 20-kHz broadcast (WWVL) on the north antenna. The original 60-kHz system (grey transmitter on south antenna) is now the primary transmitting system. The backup system consists of the blue transmitter on the north antenna. Provisions have been made to enable switching the blue transmitter to the south antenna for an additional backup mode.

NIST plans to provide the WWVB 60-kHz timing signal for the foreseeable future and has initiated planning for an upgrade that will carry this service into the 21st century. The goals of the upgrade include providing new reliable and maintainable transmitters and a 6-dB increase in radiated power. As the first part of this project, NIST funded NRaD to make a set of baseline measurements on the WWVB system, which was completed during October 1994. The details of the measurements are reported separately (Gish and Hansen, 1995), but the results are summarized in this report.

This report first provides a summary of the measurements (section 3), followed by a description of the elements of the system (section 4), starting at the input to the transmitter and proceeding out to the ends of the antenna system. At the end of each subsection, relevant findings and conclusions are presented. Section 5 provides analysis and summarizes the recommended upgrade. The final section (6) gives recommendations for immediate consideration.

3. SUMMARY OF MEASUREMENTS

Transmitting system performance measurements were made at the WWVB site in Fort Collins, Colorado, during a 2-week period starting 11 October 1994. The measurement effort is reported separately (Gish and Hansen, 1995) and summarized in table 1 below.

Table 1. Parameters of WWVB antennas.

Frequency Independent Parameters		**Primary (south)**	**Backup (north)**
Static Capacitance	C_0 (nF)	14.7	14.6
Effective Height	h_e (m)	85.5	85.5
Self-Resonant Frequency	f_0 (kHz)	94.4	94.8
Topload Capacitance	C_t (nF)	13.6	13.6
Base Stray Capacitance	C_s (nF)	1.1	1.0
Downlead Inductance	L_d (uH)	208.8	208.0
60-kHz Parameters		**Primary (south)**	**Backup (north)**
Antenna System Resistance	R_{as} (ohms)	0.803	0.913[1]
Tuning System Resistance	R_t (ohms)	0.135	0.130
Radiation Resistance	R_r (ohms)	0.462	0.462
Antenna Loss Resistance	R_{at} (ohms)	0.206	0.321
Antenna System Bandwidth	BW (Hz)	263	310
Radiation Efficiency	η (%)	57.5	50.6
Base Reactance	X_b (ohms)	–114.9	–112.9
Topload Reactance	X_t (ohms)	–186	–186
Helix Inductance	L_h (uH)	278.4	212.5
Variometer Inductance	L_v (uH)	26.4	87.0
Current Limits	I_{max} (amps)	300	200[2]

[1]The resistance of the north antenna varied when measured with a few watts. The resistance of the north antenna was estimated at transmitter power levels by transmitting into the south antenna, operating the north antenna as a parasitic, and inferring the resistance from the current ratio. With 100 amps flowing in the north antenna, the resistance measured in this way was 0.88 ohm. The corresponding loss resistance is 0.288 ohm, and the radiation efficiency is estimated at 52.5 percent. This is our best estimate of the resistance of the north antenna at transmitter power levels, but this value could vary significantly with moisture, etc.

[2]These limits are calculated for the litz wire when new assuming the existing connections are replaced. The actual limit for the existing litz wire must be determined by a heat run.

Table 1. Parameters of WWVB antennas (continued).

Mutual Impedance @ 60 kHz			**Both**
Resistance (total)	R_m (ohms)		0.377
Radiation Resistance	R_{rm} (ohms)		0.346
Loss Resistance	R_{lm} (ohms)		0.031
Reactance	X_m (ohms)		–0.652
Magnitude	Z_m (ohms)		0.750
Transmission Line		**Primary (south)**	**Backup (north)**
Characteristic Impedance	Z0 (ohms)	522	535
Electrical Length	ϕ_e (degrees)	31.3	31.7
Physical Length	ℓ (ft)	1427	1450
Attenuation (Total)	R_{at} (ohms)	0.01	0.011
20.6-kHz Parameters		**Primary (south)**	**Backup (north)**
Antenna System Resistance	R_{as} (ohms)	——	0.89
Tuning System Resistance	R_t (ohms)	——	0.607
Radiation Resistance	R_r (ohms)	——	0.054
Antenna Loss Resistance	R_{al} (ohms)	——	0.232
Antenna System Bandwidth	BW (Hz)	——	——
Radiation Efficiency	ϕ (%)	——	6.1 %
Base Reactance	X_b (ohms)	——	–477

Physical measurements were taken of the helix house and other components, variometer, helix, bushing, insulators, wires, transmission lines, etc. Earth conductivity was also measured at several sites. Measurements were taken of the coupling coils on the helices as well as the impedance on the plates of the grey transmitter. A circuit model of the entire primary transmitting system including the transmission line was developed and is included in the measurement report (Gish and Hansen, 1995).

4. SYSTEM DESCRIPTION

4.1 MODULATION FORMAT

On 1 July 1965, WWVB began broadcasting time information using a carrier level-shift modulation carrying a binary-coded decimal (BCD) time code. This time code is broadcast continuously, and the modulation is synchronized with the 60-kHz carrier signal. The modulation is formed by fullpower pulses separated by spaces having the power reduced 10 dB. The shortest full-power pulse and low-power space is 0.2 second. The longest full-power pulse and low-power space is 0.8 second. The waveform duty cycle is approximately 50 percent. The shortest pulse is 0.2 second, which implies a system bandwidth requirement of approximately 5 Hz.

4.2 TRANSMITTERS

4.2.1 Grey Transmitter

The grey transmitter appears to have been built from an AN/FRT–6 military surplus transmitter and has been nominally rated at 50 kW of output power. It is a transformer-coupled, push-pull, linear amplifier that probably operates class A or AB. The output transformer is configured for 500-ohm balanced output. This transmitter has four 3CX–10,000 triode tubes in the final stage.

These tubes are capable of a plate dissipation of 10,000 watts each, or 40,000 watts total. For a plate efficiency of 50 percent and a 100-percent duty cycle, the maximum expected output power for this transmitter, based on plate dissipation, is 40 kW. For a 50-percent duty cycle, the plate dissipation limited output power would be twice this, but there are probably other factors such as power supply output and/or voltage and current limits that would limit the maximum output power.

For the grey transmitter and the south antenna, antenna tuning is done by adjusting the helix house variometer for maximum current. With the antenna tuned for this condition, the impedance at the plates of the grey transmitter was measured and found to have a phase angle near 30 degrees.

During normal operations, the grey transmitter provided only 18 kW to the antenna (section 4.7). The plate efficiency observed for this transmitter was only 32 percent. The low efficiency is probably due to the high phase angle of the impedance at the plates of this transmitter.

4.2.2 Blue Transmitter

The blue transmitter is the backup system, and it is normally used on the north antenna. However, provisions have been made to switch this transmitter to the south antenna for a backup mode if necessary. The blue transmitter has a tuned tank circuit in the output stage and appears to operate as a class C amplifier. It has a different output impedance than the grey transmitter and requires a different number of turns for the helix coupling coil. Thus, the south helix, which can be driven by either transmitter, has two separate coupling coils, one for the grey transmitter and one for the blue transmitter.

The blue transmitter uses 12 3CX–2500 tubes, each rated for 2500 watts plate dissipation, or 30,000 watts total. Assuming 70-percent plate efficiency, typical for a class C amplifier, the plate dissipation output power limit for a 100-percent duty cycle would be 43 kW and twice this for a 50-percent duty cycle. Again, there will probably be other factors limiting the maximum output power. However, considering only plate dissipation, the blue transmitter should be able to generate nearly the same power as the grey transmitter. No data were taken for plate dissipation or plate efficiency on this transmitter.

4.2.3 Transmitter Summary

The impedance matching in the helix houses could probably be adjusted such that both transmitters could operate at higher plate efficiency and generate more power. The transmitters are obsolete, have inadequate documentation, are becoming progressively more difficult to maintain, and must eventually be replaced.

4.3 TRANSMISSION LINES

There are two transmission lines, one for each antenna. Both lines are above-ground, two-wire balanced lines with nominal impedance of 500 ohms. These lines have little attenuation and seem to be in excellent condition. It is possible that some of the increased losses observed during icing conditions may be due to increased dielectric loss in these exposed transmission lines (see section on icing).

The modern transmitters available for the upgrade are designed to use 50-ohm coaxial transmission lines, and as part of the upgrade the balanced lines should be replaced with 50-ohm transmission lines. Coaxial lines are compatible with a coupling coil type of matching system because they are unbalanced. This type of matching is easily adjustable if a variometer is used (section 4.4.3).

4.4 HELIX HOUSE

The two helix houses contain the tuning and matching systems for each antenna. The major part of the tuning is done by a large air core coil (or helix) wound with litz wire.

The construction of the helix houses are identical: steel frame construction covered with galvanized steel sheets. They are in good condition, and it is not necessary to replace them.

Each helix is wound on a vertical cylindrical porcelain structure. Several levels of horizontal porcelain support arms extend out from the cylinder. Five of these porcelain arms per level are equally spaced around the cylinder. The litz wire windings are supported by these horizontal arms. The windings are in thin layers called pies, each wound on a set of porcelain arms. This type of coil is sometimes called a “piewound” coil.

Inside each helix house, a wooden scaffold has been built around the helix to provide access to upper levels of the helix for inspection and cleaning. At the higher power levels that will result from the upgrade, the scaffolding will become a fire hazard and must be removed. It is recommended that a rolling ladder be built to provide the required access. There are other miscellaneous items in the helix houses that should be removed. Also, there are rodents living in both helix houses that should be eliminated.

For the upgrade power level anticipated, it will be necessary to modify the insides of the helix houses to provide a keyed transmitter interlock system for personnel safety. A fenced inside area around the door should be provided that will allow access to only a limited area near the door when transmitting. The helix house controls and monitoring equipment should be moved within this access area. A keyed, interlocked gate would provide access to the rest of the helix house but only when not transmitting.

It is desirable to modernize the helix house control and monitoring systems, including the antenna current monitor and variometer position control and monitor. Fiber-optic lines should be installed at the same time as the new transmission lines to support the monitoring and control system. The monitoring systems should include at least a fire and smoke alarm and probably fire protection since the station operates totally unattended at night and on weekends. An autotune system is necessary, and an automatch system is highly desirable.

4.4.1 South Helix

The south tuning helix has 16 turns wound with three parallel pieces of 3/4-inch litz wire. The current limit on each piece of litz (if new) would be slightly over 100 amps rms, for a total nominal rating of 300+ amps. The connectors used on the litz are not up to this rating and need to be replaced with elephants-feet connectors. This litz may well operate at the 300-amp limit. However, it will be necessary to determine the acceptable current limit by a heat run, whereby the current is gradually increased and the temperature of the helix and connections are periodically checked.

For the upgrade, it is necessary to replace the litz wire connections, and it is desirable to replace the litz, if within budget.

4.4.2 South Variometer

In both helix houses, the variometers are connected in series between the low-voltage side of the helix and ground. The variometer provides a variable element to fine tune the antenna system to resonance. It is adjustable to compensate for environmental variations such as wind or rain that

slightly change the antenna resonant frequency. These variometers are motor-driven and can be operated remotely from the transmitter building. They have a servo system that senses phase between antenna current and an atomic standard clock that keeps the antenna system tuned as environmental changes take place.

The variometer in the south helix house is wound with two pieces of 3/4 litz wire in parallel. The rotor is connected in series with the two 1/2-stator sections. For this configuration, there are four pieces of litz wire nearly in parallel, giving the variometer a rating in excess of 300 amps.

The parallel configuration greatly reduces the inductance variation available from this variometer. The station personnel indicate that during certain conditions (see section on icing) the antenna parameters move beyond the range this variometer can compensate. Under the present operating condition of 150 amps antenna current, this variometer could be converted to the series configuration for greater tuning range. However, the minimum inductance is greater for the series configuration, and changing to this configuration would require removing some helix windings to keep resonance at 60 kHz.

For the upgrade, it is recommended that a new larger tuning variometer having a larger tuning range and the capability to handle at least 330 amps current be procured. The existing variometer may possibly be used as the coupling variometer.

4.4.3 South Matching System

The matching from the 500-ohm balanced transmission line to the nominally 1-ohm unbalanced antenna system is done using an air core transformer. It consists of a few turns of single litz wire wound around the helix forming the primary, which is inductively coupled to the main tuning helix that forms the secondary.

In the south helix house, there are two primary windings, one for the grey transmitter and one for the blue transmitter. A switch has been provided so that the two windings can be remotely selected at the transmitter building. The primary windings are connected through series capacitors directly across the transmission line. The capacitors are presumably included in order to cancel the transformer leakage inductance.

The primary purpose for this matching system is to convert the antenna impedance to the line impedance. In this case, it also converts from the unbalanced antenna to the balanced transmission line. A major drawback to this type of matching system is that the impedance transformation ratio is fixed and cannot easily be adjusted. For the existing WWVB system, the impedance presented to the line is far from the line impedance. Most of the adjustment to increase transmitter output power and plate efficiency, mentioned in the transmitter section, amounts to changing this ratio. However, adjustment involves winding new primary turns and testing them by trial and error. The fixed matching system has no way to adjust for environmental changes to antenna resistance.

For the upgrade, it is recommended that this fixed matching system be replaced with a coupling variometer system that allows ease of adjustment and is compatible with the 50-ohm unbalanced transmission lines recommended. A schematic of the recommended matching system is given in figure 1.

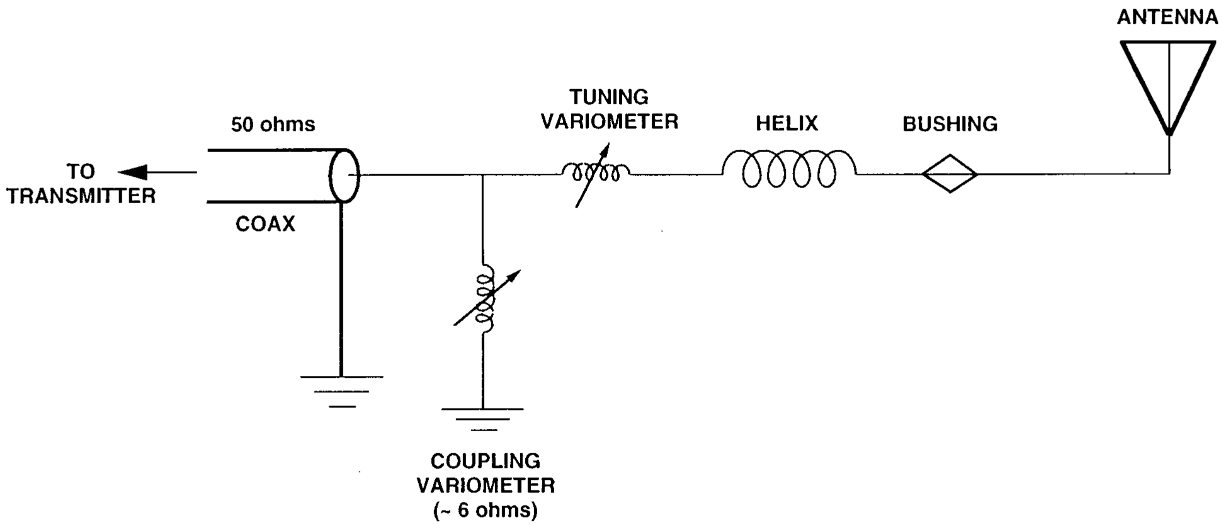

Figure 1. Recommended helix house matching system.

4.4.4 Bushings

The feedthrough bushings are identical in both helix houses. The purpose of the bushing is to pass the antenna current from the high-voltage side of the helix through the grounded helix house walls to the antenna. The bushing must be appropriately rated to handle the high voltages and currents that occur at this location.

The WWVB feedthrough bushings are mounted vertically on the roof of the helix house directly above the helix; this is the optimum position. The existing bushing without modification should be able to handle approximately 50 to 70 kV rms wet. An analysis of the actual rating is beyond the scope of this effort. The bushing as it stands should be adequate for the upgrade, but this should be confirmed by analysis.

4.4.5 North Helix

The north helix is similar to the south helix except for a taller porcelain cylinder, which has two separate sets of secondary windings, one for 60 kHz, and a second larger set of windings for 20 kHz. The windings for both frequencies are built from two parallel pieces of litz wire and therefore have a current rating of only 200 amps. It would be possible to remove the 20-kHz windings and use that litz wire to rewind the 60-kHz windings with three pieces of litz in parallel to increase the current rating to that of the south helix.

The north helix house is the backup system and as such is not operated often. However, there is no reason that this antenna and helix house should be any less capable than the other. It is recommended that this helix be upgraded to be the same as the other helix house. This would provide complete redundancy, enabling regularly scheduled maintenance on both sides. Upgrading the two antenna systems to be the same allows simultaneous transmission on both antennas, which has some other advantages (see section 5.4).

For the upgrade, it is recommended that the 20-kHz windings be removed and the 60-kHz windings rewound to provide the capability of at least 330 amps. The increased capability could be provided either by adding the litz from 20-kHz windings in parallel with the existing 20-kHz windings or, preferably, using new litz if within budget. As in the south helix house, the connectors must be replaced.

4.4.6 North Matching System

The north helix house has only one primary winding, used for the blue transmitter, which is connected directly across the transmission line through some series capacitors that presumably cancel the transformer leakage inductance. Recommendations are the same as for the south matching system.

4.4.7 North Variometer

The tuning variometer is identical with the one in the south helix house except that it is configured with the stator and rotor in series. The series connection has a greater range of inductance change than the parallel configuration. However, the series configuration results in a lower current rating (200 amps) since only two litz wires are in parallel.

For the upgrade, this variometer should be replaced with a larger one that provides a greater tuning range and an adequate current rating. The existing variometer may possibly be used as the coupling variometer.

4.5 GROUND SYSTEM

No documentation is available for the antenna ground system. Several wires were traced using the NRaD ground wire tracker. The ground systems consist of about 300 wires, approximately 1300 feet long, buried radially to the helix house. The ground systems appear to be identical for each antenna system. The wires were dug up at a few locations and found to be buried at a depth of 8 to 10 inches.

The buried ground radials are connected to a peripheral bus consisting of a 1/2-inch-diameter copper cable buried around the outside of the helix house foundation. The peripheral bus is connected to copper straps that enter the cement foundation at approximately 6-foot intervals. These copper straps are hidden in the cement but are presumably connected to three larger copper straps coming out of the cement floor inside the helix house. These straps are connected to the low side of the tuning helix and form the RF ground inside the helix house. No drawings of this portion of the ground system or these hidden connections are available.

The buried radial conductors are tinned copper braid, which has become somewhat brittle over the years but appears to be in generally good condition. Eventually these conductors will need to be replaced, but it is not necessary at this time.

Station personnel indicate that the original ground system was inspected many years ago. The original wires had deteriorated significantly due to corrosion, attributed to the high level of alkalinity in the soil. A new radial ground system was installed using tinned wires for protection against corrosion. No drawings or documentation of the ground system upgrade are available. However, some old photographs indicate that the original ground system was a rectangular grid with large spacing between wires. The photographs confirm that the newer ground system has approximately 300 radial wires.

As the ground system deteriorates, antenna resistance increases, resulting in less radiation efficiency. An excellent method of monitoring ground system condition is to keep records of antenna resistance. An analysis can then be made to determine when it is cost effective to repair or replace the ground system. When resistance increases enough to affect the power bill significantly, the ground system should be replaced. Increased antenna resistance can also be an early symptom of insulator problems. Antenna system resistance can be measured without disturbing operation by using the transmitted signal. The Navy uses a computer-based resistance monitoring system called

Antenna Monitoring System (AMOS) at some LF sites. This system can be configured to do autotuning and automatching.

4.6 ANTENNA SYSTEMS

The two antennas are identical top-loaded monopole antennas, each located approximately 1500 feet away from the transmitter building. The antenna toploads are diamond-shaped panels supported by four 400-foot towers with a dogleg downlead from the center of the panel. The panels have eight wires running the long way of the diamond, forming the main portion of the topload panel. These wires are supported in the center by a heavy support cable that crosses the diamond. This type of antenna, although usually with one or more rectangular sections, is sometimes referred to as a triadic antenna and was common at the time it was built.

Each corner of the topload is supported from the tower with an insulated halyard cable that runs down to a counterweight at the tower base. The antenna downlead has a counterweighted dogleg configuration that leads from the center of the panel to the helix house bushing. The dogleg allows for the panel movement that occurs with wind. The downlead is made up from a six-wire cage suspended from the center of the cross support cable.

The site drawing (figure 2) shows a top view of these two antennas, originally called pilot antennas. The other antenna in the figure labeled “High Power Station” (a true triadic) was never constructed.

The geographic coordinates for the center of each of the antenna were measured by a military GPSS receiver (accuracy better than ±10 meters) and compared with those provided by NIST (see table below).

GPSS (WGS 84)	NIST
North Antenna 40° 40.857′ north 105° 03.034′ west	North Antenna 40° 40.855′ north 105° 03.000′ west
South Antenna 40° 40.475′ north 105° 02.688′ west	South Antenna 40° 40.472′ north 105° 02.659′ west

The GPSS and NIST coordinates agree remarkably well, having a total difference between them of 205 feet for the north antenna and 176 feet for the south antenna. Most of this error is in the east-west coordinate, with GPSS indicating both antennas are west of the NIST coordinates. The separation between antennas is nearly the same for both sets of coordinates. Based on the NIST coordinates, the distance between antenna centers is 950.8 meters on a direction of 312 degrees true, or about 0.19 wavelength at 60 kHz.

4.6.1 Feed Cages

The feed cages consist of six aluminum wires formed into a cage around circular spacers having a diameter of 5 5/8 inches. These cages provide the voltage and current-carrying capability with a minimum of structural weight. The feed cage on the south antenna has been replaced after breaking and falling down during a wind storm. The old cage is lying in the south helix house.

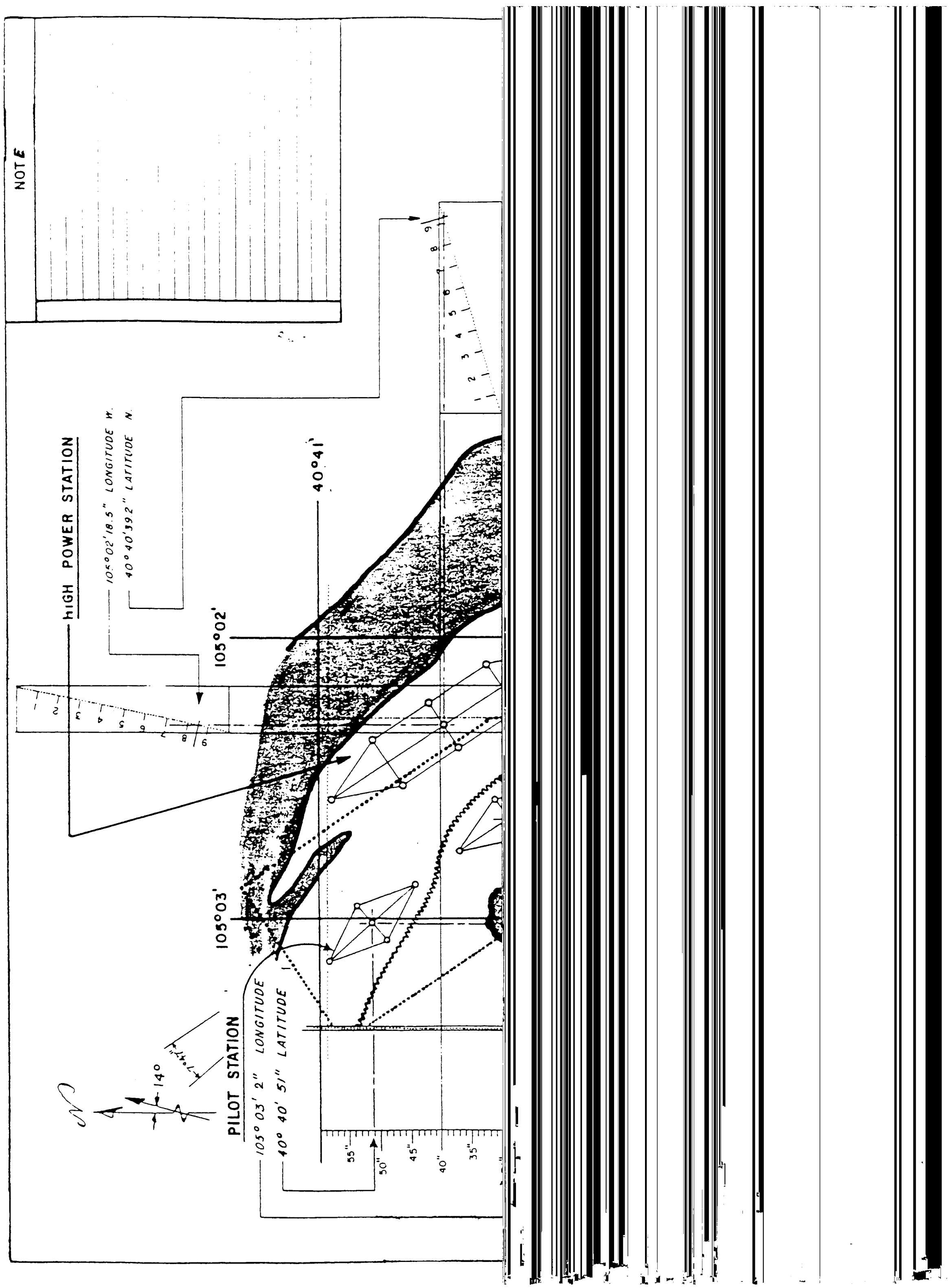

Figure 2. WWVB Fort Collins site plan.

4.6.2 Topload Panels

The topload panels are made up of 3/4-inch cables shackled together with electrical jumpers across the mechanical connections. These cables have been in place for about 35 years and should be lowered for repair and inspection.

All mechanical connections should be taken apart and worn parts replaced. Where appropriate, all mechanical connections should be coated with a conducting grease (penetrox) prior to reassembly.

4.6.3 Strain Insulators

The strain insulators used throughout the whole antenna system are smooth stick porcelains. They are made from a 4-inch-diameter hollow porcelain piece about 60 inches long. This type of insulator can withstand on the order of 100 kV rms with the right corona rings. These insulators have porcelain in tension, and a failure of the porcelain results in a structural failure. There are two insulators in parallel, used for structural strength, at the topload panel corners that connect to counterweights.

The insulators as well as the rest of the structure have been in place for about 35 years. The Navy has experienced some structural failures with this type of insulator after lifetimes of about 30 years, particularly in cold climates. *It is strongly recommended that these insulators be replaced as soon as possible.* This could be done at the same time that the topload panels are lowered for inspection and repair.

4.6.4 Fail-Safe Guy Insulators

The fail-safe guy insulators are of the compression cone type made by Lapp. There is only one insulator per guy; the purpose of the insulators is to keep circulating currents from flowing in the loops formed by the tower, guy wires, and ground. This increases the antenna effective height and efficiency slightly. Some structural failures have occurred with a similar type of insulator after many years of service; this has occurred more often in cold climates. It is recommended that these insulators be replaced with another type of fail-safe in the near future.

4.6.5 Towers and Guy Wires

The towers and guy wires appear to be in good condition but should be periodically inspected by experts.

4.6.6 Radiation Efficiency

The south antenna has a radiation efficiency of 57.5 percent; this is excellent considering the frequency and tower height.

The north antenna resistance varied when using the low-power measurement system. This variation may indicate contamination or some other insulator problem. The north antenna resistance at transmitter power levels was estimated as part of the mutual impedance measurement. The resistance estimated in this way was less than that indicated by the low-power measurements. Using the estimated resistance at transmitter power levels, the north antenna has an estimated efficiency of 52.5 percent. It would be useful to remeasure the antenna resistance after replacement of the insulators to ensure that this effect has been eliminated.

4.7 NORMAL OPERATING PARAMETERS

Typical operation observed during the testing period while using the grey (primary) transmitter and the south antenna resulted in 150-amp maximum antenna current. Other parameters

corresponding to this power level are given in the table below. "Max" refers to the modulation maximums. Note that the duty cycle for the modulated waveform is 50 percent, so the average powers are one-half of those given below.

Typical Operation
Gray Transmitter

Antenna Current (max)	150 amps (rms)
Power to Antenna (max)	18,113 watts
Power Radiated (max)	10,350 watts
Base Voltage (max)	17,550 volts (rms)
Topload Voltage (max)	28,350 volts (rms)
Plate Voltage (max)	5,700 volts (rms)
Plate Current (max)	10 amps (rms)
Plate Dissipation (avg)	28,500 watts
Plate Efficiency	–31.8 %

The antenna current was monitored by using Pearson current probes with an accuracy of +1/2, –0 percent, and the HP digital multimeters with an accuracy of ± 1 percent at LF. Thus the power delivered to the antenna in the above table is accurate. The station's existing current monitors were calibrated, and the data are included in the measurement report (Gish and Hansen, 1995).

One conclusion is that the grey transmitter is delivering only 18-kW peak power, of which 10 kW is radiated. A 6-dB increase implies 40 kW radiated and requires an antenna current of 300 amps.

Another conclusion is that the plate efficiency of the grey transmitter is unusually low. The transmitter is operating in linear mode and should have an efficiency on the order of 50 percent (class A) or higher (class B). The plate efficiency was calculated by using the transmitter plate current and voltage meters, which may not be calibrated accurately and could cause an error in the estimate. However, the plate efficiency could actually be that low, caused by the high phase angle in the plate circuit.

5. PROPOSED UPGRADE

5.1 POWER LIMITATIONS

Accurate determination of the power limitation for the existing antenna systems at WWVB is beyond the scope of this task. However, in an effort to assist in the preliminary decisions for the upgrade, an estimate has been made of the system operating parameters for 40 and 50 kW radiated from a single antenna.

5.1.1 Operating Parameters for 40 kW Radiated

The calculated current limit for the litz wire in the tuning system located in the primary helix house is 300 amps. To operate at this current, the existing litz wire connectors must be replaced. Since the litz is old, this limit should be verified by performing a heat run prior to commencing operations at the higher level. The actual limit may be somewhat less than 300 amps if the litz insulation has deteriorated with age.

Assuming the full 300 amps, the resulting voltages and powers are given below. Note the voltages and currents are rms values occurring during modulation maximums. The powers stated are for modulation maximums, and the average is half of that stated because of the 50-percent duty cycle.

Single Antenna Operating Parameters
40 kW Radiated
300 amps@tokHz

Antenna Current	300 amps (rms)
Base Voltage	35.1 kV (rms)
Topload Voltage	55.9 kV (rms)
Transmitter Output Power	72.9 kW
Radiated Power	41.4 kW
Helix House Losses	12.1 kW

The base voltage of 35.1 kV is well within the capability of the existing bushing and downlead. However, the corona ring and other grading hardware at the top of the helix will need to be upgraded, and the scaffolding around the helix must be removed.

The topload voltage of 55.9 kV gives a nominal surface electric field (gradient) on the 3/4-inch diameter topload wires of 0.60 kV/mm, which is well below the wet corona onset level. This gradient was calculated by using a simple formula that applies near the center of a span. The gradient on the wires near the towers will be higher and should be determined by computer modeling as a part of the upgrade design. It is very likely that the gradient at that location will be the determining power limitation for the WWVB antenna systems.

The existing topload insulators appear to be able to withstand the topload voltage. However, it is recommended that they be replaced due to age (see section 4.6.3).

The peak output power of 72.9 kW will require a new transmitter having a peak power rating of 80 kW or more and average power rating of 40 kW.

The 6-kW average power dissipated in the helix house will require a new forced-air ventilation system.

5.1.2 Operating Parameters for 50 kW Radiated

If the litz is upgraded to cable that can handle 330 amps, 50 kW can be radiated by either antenna. The operating parameters are given below. Note that power, voltages, and currents are the values that occur during the modulation maximums.

Single Antenna Operating Parameters
50 kW Radiated
330 amps@60kHz

Antenna Curren	330 amps (rms)
Base Voltage	37.9 kV (rms)
Topload Voltage	51.5 kV (rms)
Input Power	87.4 kW
Radiated Power	50.3 kW
Helix Power	14.7 kW

The comments for these operating parameters are similar to those made for 40-kW operation. However, an even more powerful transmitter would be needed.

The conclusion is that a single antenna can handle the radiated power level desired. However, to be sure, a computer analysis of the topload gradients is recommended.

5.2 UPGRADE TRANSMITTER OPTIONS

Based on the design goal for the upgrade of 40 to 50 kW radiated, a transmitter having a nominal peak power rating of 80 to 90 kW and an average power rating of 40 to 45 kW would be adequate. There are two practical transmitter options that would support this upgrade.

5.2.1 Navy Surplus AN/FRT–72

The AN/FRT–72 is the existing Navy LF transmitter rated at 50-kW average and 100-kW peak envelope power (PEP) and is capable of operation on frequencies between 30 kHz and 150 kHz. Two of these transmitters would be required to provide the redundancy needed for continuous operation. The Navy has several of these transmitters in storage and is expected to deinstall several more in the next year or two. It is likely that the Navy will provide two of these transmitters for WWVB. However, NIST would have to provide for shipping and installation costs. One drawback is that it could take some time for the Navy to release these transmitters.

The AN/FRT–72 was made by Continental Electronics, Inc., of Dallas, Texas. It is air cooled, has excellent documentation, is still supported by the manufacturer, and has been a very reliable transmitter for the Navy. This transmitter unmodified will come close to meeting the requirement. The 100-kW PEP rating is for very low duty cycle waveforms. Because of the relatively long pulses in the BCD time code format, the AN/FRT–72 will probably not be able to provide the full 80-kW maximum power during modulation maximums without modification to the power supply, but it may come close.

When properly matched, this transmitter operates at 40- to 50-percent plate efficiency and has an estimated overall efficiency of 30 to 40 percent. Therefore, 40-kW average output would provide 100-kW continuous input power. At 7 cents per kilowatt hour, this amounts to a yearly power bill of $61,320 ($5,110 per month).

With two transmitters installed, it is recommended that a switching matrix be installed to allow either transmitter to be connected to either antenna. The switching matrix should have provisions for interlocks and should also allow for simultaneous transmission from both antennas. A dummy load should be provided for maintenance of one transmitter while the other is on the air. However, operating both transmitters at once will have an impact on the prime power requirement.

5.2.2 ESI Solid State

Electrospace Systems, Inc. (ESI) of Richardson, Texas, is supplying a new LF transmitter to the Navy termed the AN/FRT–95(a), which has a power rating of 250 kW and operates in excess of 80-percent overall efficiency. This transmitter is made up of nominal 50-kW units. The price of these units is uncertain but can be expected to be at least $4 per watt, or $200,000 per unit. A minimum of four units would be needed to provide some backup capability, and a rough price estimate for this transmitter is around $800,000.

This new transmitter is currently being tested at the Navy's VLF site in Puerto Rico with somewhat mixed results. Better information on the expected cost of operating and maintaining this transmitter will be available after the tests are finished.

The input power required for this transmitter is about half of that for the AN/FRT–72. This means that the available prime power requirement is also half that for the AN/FRT–72, which will reduce or eliminate the prime power upgrade costs. The power bill is also estimated to be one-half for an estimated savings of $30,660/year ($2,555/month).

This amount of savings would not normally justify the capital expenditure required for the new transmitter. However, costs for obtaining the AN/FRT–72 and the possible prime power upgrade are not insignificant and must be considered.

5.2.3 Discussion

The cost estimate for the ESI transmitter is soft, and the cost figures for installing the AN/FRT–72 are unknown. However, given the present information, it appears that the Navy's AN/FRT–72 transmitters are the best solution.

Since it could take some time for the Navy to release these transmitters, it is recommended that the request for them be processed immediately. The first step is to contact the Navy formally by letter requesting the transmitters. The second step is to prepare a preliminary installation plan that includes estimated costs. If these costs are excessive, the ESI option could be explored.

5.3 COVERAGE CHARTS

Coverage charts have been provided for the WWVB 60-kHz transmitter in figures 3 through 5. The charts give signal in dB/uV/m and atmospheric noise in a 1-kHz bandwidth, also in dB/uV/m. The noise data are based on the NTIA (or CCIR 322–3) noise model, and the signal is calculated by using the NRaD long wave propagation (LWP) prediction code, which models the earth-ionosphere waveguide.

The radiated power was assumed to be 15 kW, but the plot can be scaled for different powers. The plots are given for July, local noon, at the transmitter, which we call the "pseudo-worst case" analysis. All data shown were calculated for 50-percent exceedance. The signal levels calculated (figure 3) compare well with previous measurements of WWVB (Milton, 1969). Note that by far the lowest signal-to-noise ratio (SNR) level in the CONUS is in the Florida Keys, –18 dB (1-kHz bandwidth) (figure 5). The weakest signal, about 21 dB/uV/m, in CONUS occurs in northern Maine, the most distant location from the transmitter. In general, the SNR level to the north is greater because atmospheric noise is less at higher latitudes (figure 4).

The weak signal in New England suggests that there may be interference at times in that area from the British 60-kHz timing signal. The extent and times of interference could be investigated with the LWP code.

If the required SNR in atmospheric noise is known, a different type of analysis can be done that gives the available hours of service per day displayed as a contour plot. The pseudo-worst case given here does not show the deep fades that occur during the day–night transition periods. It is recommended that a time availability analysis be done prior to the final decision on radiated power. This would be part of a systems engineering study that would determine the radiated power required to provide adequate service throughout CONUS and could include aspects of power management whereby the transmitter level is adjusted seasonally and diurnally to provide adequate service but minimize power costs.

5.4 PHASED ARRAY

Operation of the two WWVB antennas as a two-element array was briefly investigated. One concern was that due to the separation of the antennas, the antenna pattern variation would be fairly large, making this mode of operation impractical. For the antenna spacing and frequency, it was found that the pattern variation, for equal in-phase currents, was less than 1 dB.

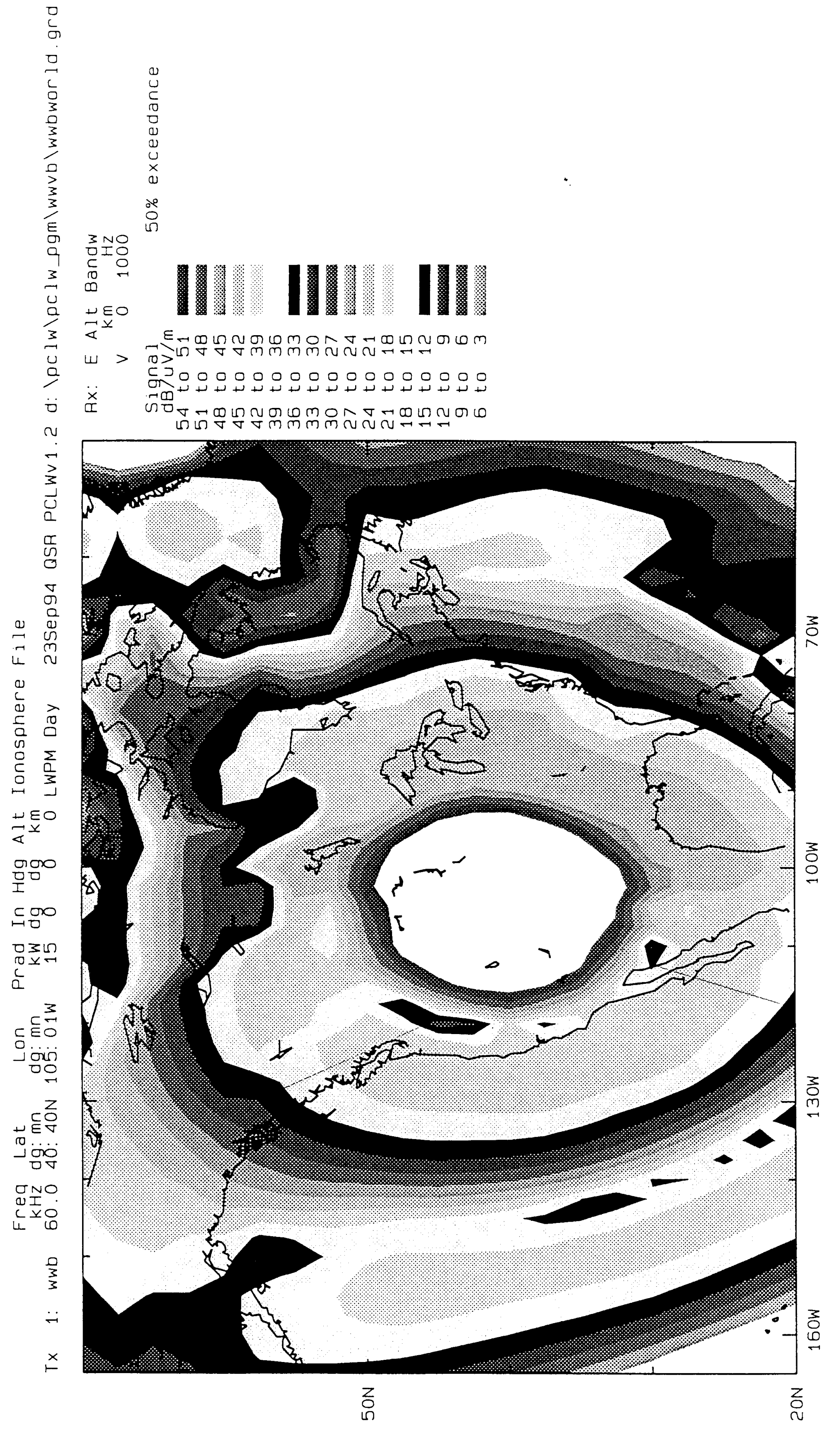

Figure 3. Calculated signal for WWVB, 15 kW radiated from Fort Collins (July local noon).

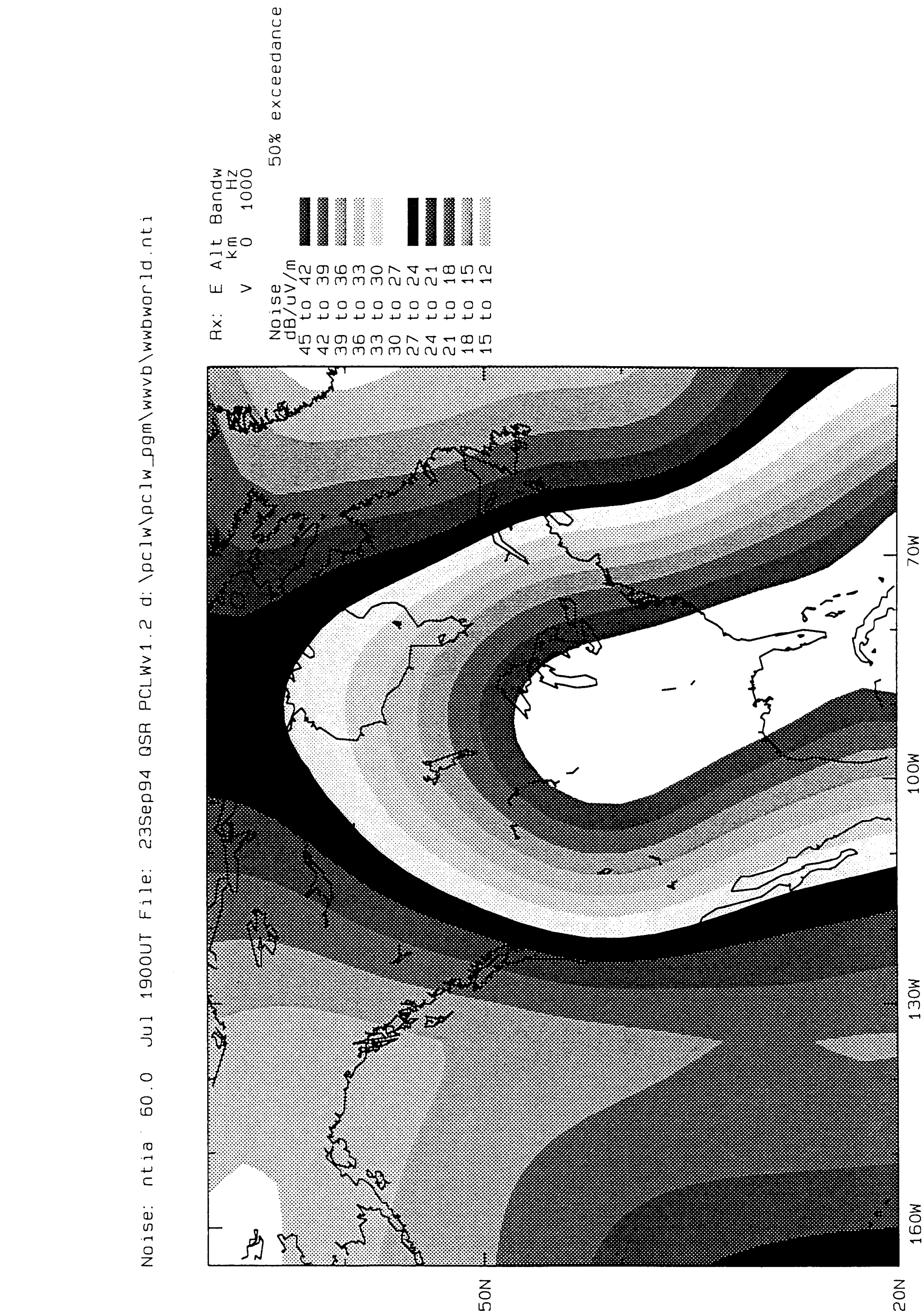

Figure 4. Calculated noise dB uV/m at Fort Collins (July, local noon).

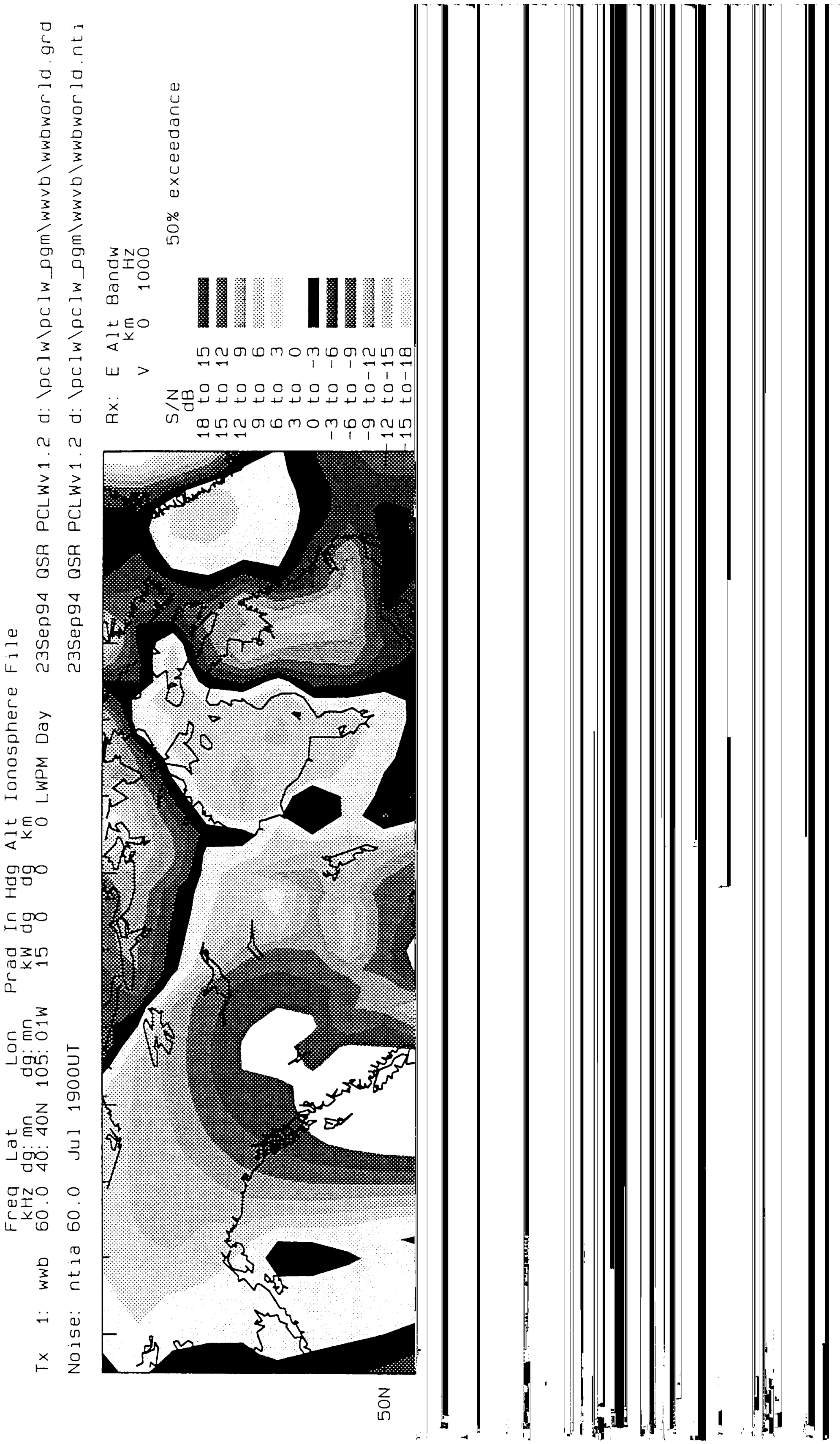

Figure 5. Calculated signal-to-noise ratio for WWVB, 15 kW radiated from Fort Collins (July local noon).

One advantage of phased array operation is an improvement in efficiency. For closely spaced, inefficient, electrically small antennas, the radiation efficiency is approximately proportional to the number of elements. The WWVB elements are relatively efficient, so the increase in efficiency is not so dramatic. The calculated efficiency for dual operation of the WWVB antennas at 60 kHz is 66.2 percent, compared to 57.5 and 52.5 percent for single operation. This is about a 20-percent improvement in overall efficiency and translates to approximately the same amount of power savings. One disadvantage is that this mode of operation would require a more complicated dual autotune–automatch system.

To first order, for voltage limited operation, the maximum radiated power limit is proportional to total topload area squared (Hansen, 1990). Thus, the two antennas together can radiate approximately four times as much power as one. This opens the door for an extra 3-dB increase in radiated power just by running both transmitters simultaneously, and another 3 dB (without increasing the stress on the antenna systems) by increasing the power of the transmitters another 3 dB.

The array pattern can be adjusted by changing the phase difference between the two elements. Adjusting the antenna current phase to provide an end-fire pattern toward the south end of the array would provide better overall coverage since more power would be directed south where the noise is greater and correspondingly less power directed north where the noise is lower.

5.5 ICING CONDITIONS

During the last winter, there were periods of prolonged icing. The icing causes the counterweighted topload panels to sag, changing antenna capacitance and hence the resonant frequency. The capacitance changes enough to exceed the tuning range for the south variometer. When this happens, the station must go off the air. During these incidences, the operators noticed that the antenna current was reduced considerably as this process went on. The current reduction indicates increased losses that could be dielectric loss on the transmission line and antenna and/or leakage loss on the insulators. The use of the coaxial cable and new antenna insulators having longer leakage paths will help reduce this effect. The adjustable matching system proposed will be able to follow changes in antenna resistance and couple full transmitter power into the antenna. These improvements may make this problem manageable.

A deicing system could be designed to eliminate this problem. For such a system, the antenna conductors are rigged in such a way to allow for a 60-Hz current through them for deicing. Both antennas would be rigged in this manner. Deicing would proceed on one antenna while operations continued on the other. After deicing one antenna, the roles of the antennas would be reversed, allowing nearly continuous operations. The amount of deicing power required is a minimum of 1.6 watts per square inch of antenna conductor. The overall power required for one panel will approach a megawatt for one panel plus the downlead. Installation and operation of such a system is very expensive and is not recommended unless absolutely necessary.

5.6 RECOMMENDED UPGRADE

The upgrade recommended below will result in a 6-dB increase in maximum radiated power, or a minimum of 40 kW radiated. It will provide adjustable matching. It will have complete redundancy to enable continuous operation of one system while the other system is being maintained. This complete redundancy also allows the possibility of dual-array operation for further increases in radiated power. The major aspects of the recommended upgrade are listed below.

Recommended Upgrade List

1	New transmitter(s) 50 ohm (probably two AN/FRT–72s)
2	Facility upgrades (air, prime power)
3	RF switch matrix
4	Optional dummy load
5	50-ohm coaxial transmission lines
6	Coupling variometers
7	New larger tuning variometers
8	Litz wire reconfiguration or replacement
9	Helix house ventilation
10	Helix house safety apparatus, screen fence, keyed interlock
11.	Helix house monitoring system, current, fire, arc, and autotone, automatch, optional antenna resistance monitor
12.	New antenna insulators (required with or without upgrade)

6. RECOMMENDATIONS

1. Replace the insulators in the toploads and feed cages as soon as possible. Also replace the guy fail-safe insulators with a new fail-safe insulator of a different type.
2. Inspect and repair all electrical aspects of both antennas as required. The topload panels and downlead cages must be inspected. All electrical connections and jumpers should be taken apart, cleaned, repaired or replaced if necessary, and coated with conducting grease prior to reassembly.
3. The towers and guy wires should be inspected by structural experts.
4. Start the process of obtaining two AN/FRT–72 transmitters from the U.S. Navy as soon as possible.
5. Develop a plan for the recommended upgrade. This plan should consider transmitter physical location, floor loading, air conditioning loads, cooling air requirements, prime power availability, as well as the RF considerations such as transmission lines, power and voltage limitations, etc. The plan should include a time availability propagation analysis to determine the expected coverage for the increased radiated power.

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